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ABSTRACT

This report provides a quantitative coverage analysis of a draft Application Protocol (AP) for numerically controlled machining process plans in an international standard for product data representation and exchange. The analysis addresses the effectiveness of this AP by analyzing the coverage of the data model in the AP to the interface data from several commercial computer-aided process planning systems and numerical control programming systems. It is necessary to evaluate how much machining process information can be unambiguously exchanged among commercial systems in order to determine if the AP should proceed through the standards process as is or if there should be further changes. The report documents several measurement techniques, describes measurement results, and reveals some limitations found in the AP.

Keywords: NC programming, STEP, application protocol, data exchange, numerical control, process planning, product data modeling, systems integration.

1 INTRODUCTION

Standard representations of manufacturing process plan data are essential to build mechanisms for open data exchange among manufacturing applications, as well as to guide the new development of commercial manufacturing software systems. ISO 10303 Part 213 [1] is an Application Protocol (AP) for representing the data entities used in process plans for numerically controlled machined parts, and it is in Final Draft Internatioal Standard (FDIS) status. ISO 10303 is commonly referred as STEP. AP 213 is intended for archiving, exchanging, and sharing information between dissimilar Computer-Aided Process Planning (CAPP) systems and Numerical Control (NC) programming systems. To better understand the applicability of the protocol, the first step is to evaluate how well the AP captures commercial NC process plan data. An initial analysis of AP 213 was conducted in a NIST project, which addressed integration issues in a collected suite of manufacturing tools. Some missing concepts, such as tool name, the process plan creation date, action name, etc. were found [2]. This report provides a more detailed analysis of the coverage of AP 213 on commercial systems is conducted, and the results are documented in this report.

As a STEP qualification requirement, it is required that pilot implementations of the AP on commercial process planning and NC software systems be performed before the AP 213 reaches the International Standard status. This report provides necessary information to the STEP qualification team members to assess the future direction of this AP. It is not the intent of this report to recommend whether AP 213 should advance in the standards process or not. In a pilot implementation project[1] performed at the National Institute of Standards and Technology (NIST), four commercial software systems were available to us, two CAPP software systems and two NC programming software systems. Companies that sold these four systems collaborated with us in analyzing AP 213. A substantial amount of data could not be translated from one system to another system using the data entities defined in AP 213. This was our motivation to conduct a thorough coverage analysis on AP 213. The analysis process included the following tasks: mapping system interface data to the AP 213 Application Reference Model (ARM), calculating coverage ratios, and analyzing the coverage of AP 213 over the four software systems. Five major measurement factors, or ratios, were developed to evaluate the coverage. Their definitions can be found in Section 4.1. These five ratios are as follows: (1) the ratio of the number of data structures of a commercial system within the scope of AP213 to the total number of data structures in that commercial system's interface, (2) the ratio of the number of data structures in a commercial system that are completely and unambiguously mapped to the AP 213 ARM to the total number of data structures (in that commercial system) that are within the AP 213 scope, (3) the ratio of the number of AP 213 ARM entities that are ambiguously mapped to a system's data to the total number of the AP 213 ARM entities, (4) the ratio of the number of data structures in a commercial system that are not covered by AP 213 to

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[1] This AP 213 Coverage Analysis is a project within the Systems Integration for Manufacturing Applications program (SIMA), initiated as part of a Federal initative on High Performance Computing and Communications. SIMA is supporting manufacturing systems integration technologies, development and testing of interface specifications for manufacturing systems, application of high performance computing and networking technology to integrate design, planning, and production processes, and testbeds for achieving cost-effective application of advanced manufacturing systems and networks.

the total number of the structures in that commercial system , and (5) the ratio of the number of AP 213 ARM entities used in mapping to the total number of ARM entities. A concise statistical analysis was also performed by means of a data table to reveal the coverage variations of AP 213 in all four commercial systems. Limitations in the ability of AP 213 to support data exchange are described in the analysis .

In addition to this introduction, Section 2 provides an overview of AP 213. Section 3 describes the four commercial CAPP and CAM software systems. Section 4 describes the methods used in the analysis and the results from the coverage analysis. Finally, Section 5 concludes this report.

2 AN OVERVIEW OF AP 213

STEP AP 213 is an application protocol, which specifies data formats to represent computer-interpretable process plans for producing discrete parts using numerically controlled machines. The intent of this application protocol is to enable the exchange of machining process plan data among dissimilar CAPP and NC programming systems.

A numerically controlled machining process plan is a set of machining operations with a list of tools, setup instructions, and machining center specifications. The plan is used by NC programmers to create tool paths and NC programs which, when executed, drive the tool motion to remove material from a workpiece.

AP 213 specifies the data interface between process planning and NC programming systems as opposed to the data necessary to perform the process planning functions. According to the scope statement in the draft standard, AP 213 is intended to describe and represent the following information:

- Information from the planning activity that is contained in the NC process plans for machined parts
- Task instructions required to manufacture a part using NC machine tools
- Required NC programming information specified in the process plan

- In-process inspection information specified in the process plan
- Shop floor information specified in the process plan

AP 213 does not cover the following information:

- Information from pre-planning activities
- Production planning functions
- Actual execution of the process plan
- Continuous processes
- Make/buy analysis
- Costing
- Form features, drawings, and production illustrations
- The process planning activity
- Inspection process information
- NC source program

The AP 213 Application Reference Model (ARM) is an application-oriented data model. It defines individual entities and the relationships among them. As stated in the draft standard, the AP 213 ARM has seven functional categories, each called a Unit of Functionality (UoF):

- administrative
- manufacturing machine tool resources
- manufacturing material resources
- manufacturing tooling resources
- process activities

- product definition related data
- related shape data.

The *Administrative* UoF contains the information required for the management of a numerical control process plan. This information contains the detail to allow for the identification, release and revision of the process plan. Examples of entities specified are the information about the company and the person who developed the process plan, and the general description of a process plan. In the *Manufacturing Machine Tool Resources* UoF, entities to describe equipment and their characteristics are specified, such as machine, workstation, and machine parameter. The equipment is stationary machinery used to provide cutting power to perform material removal. The *Manufacturing Material Resources* UoF specifies entities to describe the material necessary to fabricate a machined part. Examples of the entities are material, material specification, and raw material requirement. The *Manufacturing Tooling Resources* UoF specifies entities that define cutters, cutter assemblies, fixtures, fixture assemblies, and vendor information. The tooling resource entities are associated with the material removal activity, NC programs, and the validation activity. The *Process Activities* UoF specifies entities that describe activities performed in a process plan. Machining activities like operations, steps, material removal, and machine setup are covered by this unit. The *Product Definition Related Data* UoF provides entities for describing information related to product definition and its technological requirement, such as the drawing of the machined part, tolerances in NC machining, and surface finish. The last UoF is *Related Shape Data* which specifies entities to describe geometry/shape related data of the machined part. Examples of the entities are geometric model representation and NC part object.

3 OVERVIEW OF THE FOUR COMMERCIAL CAPP AND CAM SOFTWARE SYSTEMS

Two commercial CAPP systems and two NC programming systems were available to us to study the AP 213 coverage. They were MetCapp™, CS/CAPP™, Mastercam®, and Smartcam®. These systems provided a rich set of process plan data structures to test the AP 213

ARM.

3.1 MetCapp™

MetCapp™ [3] is a CAPP system. To develop a process plan, a user has to identify workstations, machines, setups, routing sequences, and generic part feature data. The system has a machining capability database that provides automated capabilities of cutting tools selection, speed and feed calculations, processing time estimation, and operation sequencing. The process plan data are stored in .ppl (process planning language) files. Using the MetCapp™ Application Programming Interface (API) in the C programming language, one can access the process plan data. The data are listed in the first column of Table 1 in the Appendix.

3.2 CS/CAPP™

CS/CAPP™ [4] is a CAPP system that uses a relational database as a process plan data repository. A process plan is built by the system with an object model that is connected to a relational database. The process planning data in the system are organized into two basic types of objects: core planning object and attachable object. A core object is required for planning, including parts, plans, operations, and steps. The attachable objects are not required for planning. They can be attached to any core object for additional information. There are two types of them: objects that can be shared among plans and objects that cannot. Examples of these objects are tools, sketches, standard instructions, notes, materials, and NC tapes. The output data structures defined in this process planning system are listed in the first column of Table 2 in the Appendix.

3.3 Mastercam®

This system [5] is an integrated three-dimensional (3D) Computer-aided Design/Computer-aided Manufacturing (CAD/CAM) software system that facilitates geometry creation, engineering details preparation, blueprints printout, tool path generation, and NC code generation for 2 through 5 axis milling and turning. For automated tool path generation, the system has built-in material and tool libraries, tool-path simulation functions, look-ahead cutter compensation capability, cycle-time calculation functions, and feed and speed calculations.

The parameters for creating tool paths for machining a surface are stored in a parameter file with the extension of PRM. The first column of Table 3 in the Appendix has a list of the data structures used in ".prm" files.

3.4 Smartcam®

Smartcam® [6] is also a CAD/CAM system that includes automated NC code creation capabilities for 2 to 5-axis machining. It has an integrated environment for users to model the machining of a part and generate tool paths and NC codes. The system consists of several modules that work together to provide functions for producing NC machining programs from a design. These modules are CAD connection, process modeling, milling applications, and NC coding. The CAD connection module facilitates the translation of files from a number of CAD systems into the native format of the system.

The process modeling module and milling applications module together provide the graphic environment for creating a machined part model from which tool paths are generated. There is a solid model tool built in the system. Two methods for entering geometry are provided by the system: free-form geometry and profile geometry. The system also provides a group of functions for creating geometry drawings. When a model is complete, the tool path generation process starts. This includes tool path pattern selection, cutting direction, actual cutter path generation.

The NC coding module takes generated tool paths, process parameters (cutting speeds, feeds, coolant on/off, depth of cut), and an identified postprocessor to generate NC programs for a specified machine controller.

A user's application consists of two types of files that work together: a Computer Numerical Control (CNC) Process Model and Job Operations Setup.

A CNC Process Model is a dynamic, sequential tool path database. The following three components of a NC process plan are incorporated when a CNC Process Model is built:

Sequence – the order of machining operations

Properties – machining parameters such as tool selection, depth, tool offset direction, and machine control behavior are assigned to the tool path.

Geometry – elements defining the tool path, such as linear or circular cutting, rapid traverses, and lead-in moves, are added to the model.

The Job Operations Setup (JOS) is a model that is used to define process tasks. The information about the tools and operations used in machining a part is in JOS files. The JOS contains the process steps and related information, such as machine identification, part description, and material. Each process model is linked to a .jos file. The JOS links tools and operations together to form machining steps. The data structures defined in the .jos file are listed in the first column of Table 4 in the Appendix. The data is used to specify the tool, operation, material, and job data in a process plan of the machined part to create NC codes.

In summary, the system primarily uses information from the following two sources when generating NC codes:

.pm4 file – the model database to describe the geometry of the part, its sequence, and related properties.

.jos file – the job setup operations file to support the geometry by identifying information that relates to tools and operations, such as feed rates, cutting speeds, and tool sizes.

4 COVERAGE STUDY OF AP 213 ARM ON DATA STRUCTURES IN THE FOUR CAPP AND NC PROGRAMMING SYSTEMS

Mapping from application systems to the AP 213 ARM forms the base of the analyses in this section. The mapping tables are in Appendix Tables 1 to 4. They are created based on the materials found in ISO/FDIS 10303-213 and the system and interface manuals of the four software systems. A major challenge is that data representation structures of the AP 213 ARM and the four applications systems are all different although the concepts are somewhat similar. The differences are described as follows. AP 213 ARM data entities are in a networked form. Data in MetCapp™ are in a hierarchical structure. Data in CS/CAPP™ is a relational structure since the data are stored in a relational database. Mastercam® has individual data structures pertaining to surface/curve geometries and cutter/process parameters to specify tool path creation. Smartcam® data are also in data structures with links from one to another, and they are primarily used to define jobs, machining processes, surface geometries, tool motions, etc. to create the NC tool paths. Because of the diversity in systems data structures and some uncertainty about the definition of the data from the software venders, inconsistency problems in mapping may exist in the mapping tables.

The following assumptions and rules are applied to the mapping table development:

1. Only the AP 213 Application Reference Model is considered because the Model defines NC machining process plan-specific information in STEP.
2. ARM entity definitions are in Section 4 of the AP 213 document.
3. The meaning of the generic entities *Numeric_Parameter* and *String_parameter* should be referred to their superclasses. For example, entities tool_parameter, machine_parameter, process_parameter, material_parameter, and auxiliary_header_information all have subclasses numeric_parameter and string_parameter.

4.1 Coverage analysis

Computations are made to quantitatively describe the coverage of AP 213 ARM on the data structures defined in the selected software systems. Many notations are used, and they are defined as follows:

S_{ARM} : the set of all the entities defined in AP 213 ARM.

S_{UARM} : the subset of S_{ARM} that can be mapped to data structures in an application system.

S_{system} : the set of all the data structures in an application system (CAPP or NC programming).

S_{out} : the subset of S_{system} that is out of the scope of AP 213.

S_{in} : the subset of S_{system} that is within the scope of AP 213. So, $S_{system} = S_{in} \cup S_{out}$.

$S_{uncovered}$: the subset of S_{in} that is not covered by the AP 213 ARM but within the scope of AP 213.

$S_{mappable}$: the subset of S_{in} that can be mapped to corresponding AP 213 ARM entities. So, $S_{in} = S_{mappable} \cup S_{uncovered}$.

$S_{complete}$: the subset of $S_{mappable}$ that is unambiguously mapped to AP 213 ARM, i.e., all the definitions of the data structures in $S_{complete}$ match the definitions found in the AP 213 ARM.

$S_{partial}$: the subset of $S_{mappable}$ that is partially mapped to AP213 ARM entities, i.e., only some, not all, of the attributes in every data structure of an application system can be mapped to the AP 213 ARM (a data structure is only partially covered by AP 213).

$S_{ambiguous}$: the subset of $S_{mappable}$ that has the following problem: different data structures with different meanings are mapped to one ARM entity, which thus has an ambiguous definition. Consequently, ambiguity appears in the mapping. So, $S_{mappble} = S_{complete} \cup S_{partial} \cup S_{ambiguous}$.

Q: the total number of entities in S_{ARM} ($Q = 67$).

S: the total number of entities in S_{UARM} ($S \leq Q$).

T: the total number of data structures in S_{system}.

O: the number of data structures in S_{out} ($O \leq T$).

N: the total number of the data structures in S_{in} ($T = O + N$).

U: the total number of data structures in $S_{uncovered}$ ($U \leq N$).

M: the total number of data structures in $S_{mappable}$ ($N = U + M$).

C: the total number of data structures in $S_{complete}$ ($C \leq M$).

P: the total number of data structures in $S_{partial}$ ($P \leq M$).

A: the total number of data structures in $S_{ambiguous}$ ($M = C + P + A$).

R_M : the ratio of the number of system data structures mapped to AP 213 ARM to the number of the data structures that are within the scope of AP 213. ($R_M = M/N$).

R_C : the ratio of the number of completely mapped data structures to the total number of the mappable data structures ($R_C = C/M$).

R_P : the ratio of the number of partially covered data structures to the total number of the mapped data structures ($R_P = P/M$).

R_A : the ambiguity ratio ($R_A = A/M$).

R_U : the uncoverage ratio ($R_U = U/N$).

R_O : the out-of-scope ratio ($R_O = O/T$).

R_S : the ratio of the number of ARM entities used in a mapping to the total number of entities in AP 213 ARM ($R_S = S/Q$).

The meaning of the ratios is described as follows:

R_M : This measures an overall AP 213 coverage on those system data structures which are in the scope of AP 213. A measure of 1 means all the data structures in this system which should be mappable can be mapped to the AP 213 ARM format. A measure of 0 means none of the system data structures which should be mappable can be mapped to the AP 213 ARM format. A measure between 0 (excluded) and 1 (excluded) means some of the system data structures which should be mappable can be mapped to the AP 213 ARM format.

R_C : This measures the completeness of the AP 213 coverage on the system data structures which should be mappable. A measure of 1 means all the data structures in this system which should be mappable can be completely *and unambiguously* mapped to the AP 213 ARM format. A measure of 0 means none of the system data structures which should be mappable can be completely *and unambiguously* mapped to AP 213 ARM format. A measure between 0 (excluded) and 1 (excluded) means some of the system data which should be mappable can be completely and unambiguously mapped to AP 213 ARM format.

R_P : This measures the partiality of the AP 213 coverage on system data structures which should be mappable. A measure of 1 means that every data structure in the system which should be mappable has one or more attributes that can be completely and unambiguously mapped to AP 213 ARM, and one or more that cannot be so mapped. A measure between 0 (excluded) and 1 (excluded) means one or more attributes in some data structures which should be mappable cannot be completely and unambiguously mapped to the AP 213 ARM format.

R_A : This measures the ambiguity in mapping system data structures which should be mappable to the AP 213 ARM. Ambiguity occurs when more than one data structure is mapped to the same entity in AP 213 ARM. A measure of 1 means all the data in this system which should be mappable are ambiguously mapped to the AP 213 ARM format. A measure between 0 (excluded) and 1 (excluded) means some of the system data which should be mappable are ambiguously mapped to the AP 213 ARM format.

R_U : This measures the ratio of the number of the system data structures within the scope of AP 213 but not mappable to AP 213 ARM to the total number of the data structures that are within the scope. A measure of 1 means that all the data within the scope of AP 213 in this system can not be mapped to AP 213 ARM. A measure of 0 means that all the data within the scope of AP 213 in this system can be mapped to AP 213 ARM. A measure between 0 (excluded) and 1 (excluded) means some of the system data within the scope of AP213 cannot be mapped to AP 213 ARM.

R_O : This measures the ratio of the number of the system interface data that are out of the scope of AP 213 to the total number of the data structures in S_{in} (N). A measure of 1 means that all the system data structures are out of the scope of AP 213. A measure of 0 means that all the system data structures are within the scope of AP 213. A measure between 0 (excluded) and 1 (excluded) means some of the system data are out of the scope of AP 213.

R_S : This measures the magnitude of the portion of all the AP 213 entities used in mapping. A measure of 1 means that all the AP 213 entities are used in mapping. A measure of 0 means none of the AP 213 entities are used in mapping, i.e., the system is not a process planning system for NC machining. A measure between 0 (excluded) and 1 (excluded) means some of the AP 213 entities are used in mapping.

All the sets, numbers, and ratios are used in the following Section 4.2 to evaluate the AP 213 ARM coverage in each of the four systems.

4.2 The Analysis of AP 213 coverage to Interface Data Sets of Systems

The total number of AP 213 ARM entities is 67 (Q = 67). Each system's data structures are mapped to some ARM entities.

4.2.1 MetCapp™ mapping results

MetCapp™ system version 4.2 is used for this analysis. The system is an upstream application system relative to NC programming systems. Therefore the coverage of the AP 213 ARM on the output data structures defined in this system is analyzed. Data are collected from the user's manual [7] and verified by the authors using the user interfaces of MetCapp™.

There are 12 categories of data in this system. The names of the data categories are: routing, operation, feature, part information, material, workstation, tool, cutdata, pass, note, time standards, and history. The mapping between MetCapp™ data and the AP 213 ARM is in Table 1 in the Appendix.

Computations are obtained as follows. [T_i, O_i, U_i, and A_i result from counting data structures in each of the 12 categories in Table 1.]

$T = 317$ ($\Sigma_{i=1..12}\, T_i = 64 + 38 + 32 + 8 + 11 + 28 + 47 + 41 + 21 + 6 + 12 + 9$)

$O = 33$ ($\Sigma_{i=1..12}\, O_i = 13 + 7 + 3 + 0 + 0 + 4 + 0 + 4 + 0 + 0 + 2 + 0$)

$N = 284$ ($T – O = 317 – 33$)

$U = 134$ ($\Sigma_{i=1..12}\, U_i = 21 + 2 + 22 + 4 + 8 + 19 + 16 + 27 + 5 + 1 + 9 + 0$)

$M = 150$ ($284 – 134$)

$A = 114$ ($\Sigma_{i=1..12}\, A_i = 18 + 19 + 0 + 0 + 1 + 4 + 26 + 17 + 15 + 5 + 0 + 9$)

$P = 0$

$C = 36$ ($150 – 114 – 0$)

$S = 29$

$R_M = 0.53$ ($150 / 284$)

$R_C = 0.24$ ($36 / 150$)

$R_P = 0$ ($0 / 150$)

$R_A = 0.76$ ($114 / 150$)

$R_U = 0.47$ ($134 / 284$)

$R_O = 0.10$ ($33 / 317$)

$R_S = 0.43$ ($29 / 67$)

The following observations can be made:

1. Many tool-related parameters in MetCapp™ are mapped to the Tool_parameter entity in AP 213 ARM. Similarly, machine, process, and performance-related parameters in MetCapp™ are mapped to entities Machine_parameter, Process_parameter, and Performance_parameter in the AP 213 ARM. In many cases, the machine, process, or performance name in MetCapp™ is not necessarily recognizable (parseable) by another system. Therefore, the ambiguity ratio is high (0.70).

2. Less than half of the AP 213 ARM entities are used in mapping. But, a few ARM entities are over used.

4.2.2 CS/CAPP™ mapping results

CS/CAPP™ system version 2.2.4 is used for this analysis. The system is also an upstream application system. Therefore the coverage of the ARM of AP 213 on the output data structures defined in this system is calculated. Data are collected from both the Reference Guide [4] and the System Manager Utility manual [8].

There are 5 categories of data in this system. The names of these data categories are as follows: part, operation, step, tool, and sketch. The mapping between CS/CAPP™ data and AP 213 ARM is in Table 2 in the Appendix.

Computations are obtained as follows: [T_i, O_i, U_i, and A_i are resulted from counting data structures in each of the five categories in Table 2.]

$T = 23$ ($\Sigma_{i=1..5} T_i = 5 + 10 + 2 + 2 + 4$)

$O = 0$ ($\Sigma_{i=1..5} O_i = 0 + 0 + 0 + 0 + 0$)

$N = 23$ ($T – O$)

$U = 14$ ($\Sigma_{i=1..5} U_i = 2 + 6 + 1 + 1 + 4$)

$M = 9$ ($N - U = 23 – 14$)

$A = 0$ ($\Sigma_{i=1..5} A_i$)

$P = 0$

$C = 9$ ($M – 0 – 0$)

$S = 5$

$R_M = 0.39$ ($9 / 23 = 0.39$)

$R_C = 1$ ($9 / 9$)

R_P = 0 (0 / 9)

R_A = 0 (0 / 9)

R_U = 0.61 (14 / 23)

R_O = 9 (0 / 23)

R_S = 0.08 (5 / 67)

The following observations can be made:

1. From the ratios R_S and R_M, about 40% CS/CAPP™ data structures are covered by about 10% AP 213 ARM entities. This shows that the AP 213 ARM entities do not address the system data documented in this report well.
2. Detailed process-oriented information, such as process and production parameters, and resource-oriented information, such as material parameter, fixture_assembly, and tool_parameters are not mapped to CS/CAPP™. CS/CAPP™ can be considered as a more general process planning system than just an NC machining process planning system.

4.2.3 Mastercam® mapping results

Mastercam® system version 6 is applied for this analysis. The system is a downstream application system relative to CAPP systems. It takes process plan and CAD data and generates NC programs. The coverage of the ARM of AP 213 on the input data structures of the system is analyzed. Data are collected from both the Mill User Guide [9] and some example .prt and .nci system files.

There are three categories of data in this system. They are toolpath, tool, and toolpath display. The mapping between the Mastercam® system data and AP 213 ARM is in Table 3 in the Appendix. Although all the data are grouped in many structures, such as contour, drill, pocket, flowline, etc., the data that are common to the data structures are used in this study.

Computations are obtained as follows: [T_i, O_i, U_i, and A_i are resulted from counting data structures in each of the three categories in Table 3.]

$T = 136$ ($\Sigma_{i=1..3} T_i = 82 + 22 + 32$)

$O = 32$ ($\Sigma_{i=1..3} O_i = 0 + 0 + 32$)

$N = 104$ ($T – O$)

$U = 24$ ($\Sigma_{i=1..3} U_i = 18 + 6 + 0$)

$M = 80$ ($N - U = 104 – 24$)

$A = 79$ ($\Sigma_{i=1..3} A_i = 64 + 15$)

$P = 0$

$C = 1$ ($M – 0 – 79$)

$S = 5$

$R_M = 0.77$ (80 / 104)

$R_C = 0.01$ (1 / 80)

$R_P = 0$ (0 / 80)

$R_A = 0.99$ (79 / 80)

$R_U = 0.23$ (24 / 104)

$R_O = 0.24$ (32 / 136)

$R_S = 0.08$ (5 / 67)

The following observations can be made:

1. The data that are used to define the cutting process and tool paths are mapped to one single ARM entity – process_parameter. Since different systems use different process parameter names, the process parameter names from CAPP systems can not be recognized by this system. No NC machining process vocabulary is defined in AP 213 or in STEP.
2. The NC process and tool definitions are the major input to this system. These are specific concepts that are different from one tool to another. For example, cutting speed, coolant on/off, depth of cut are specific and different process parameters. AP 213 ARM does not

provide a precise information model for the exchange of these definitions from one system to another.

4.2.4 Smartcam® mapping results

Smartcam® system version 9 is applied for this analysis. The system is a downstream application system of process plans; therefore, the coverage of the ARM of AP 213 to the input data structures of the system is analyzed. The data structures for this analysis are collected solely from .jos files.

There are 10 categories of data in this system. They are as follows: header, job information, work cell, material, step, tool assignment, tool assembly, operation, and tool. The mapping between the Smartcam® system data and AP 213 ARM is in Table 4 in the Appendix. Although the data are grouped in many structures in tool assemblies, tools, and operations such as end mill assembly, ball mill assembly, end mill, ball mill, rough milling, and finish milling, etc., the data that are common to the data structures in the three groups (tool assemblies, tools, and operations) are used in this study.

Computations are as follows: [T_i, O_i, U_i, and A_i are resulted from counting data structures in each of the 10 categories in Table 4.]

$T = 103$ ($\Sigma_{i=1..10}\ T_i = 8 + 13 + 8 + 3 + 8 + 12 + 5 + 6 + 20 + 20 = 103$)

$O = 0$ ($\Sigma_{i=1..10}\ O_i = 0$)

$N = 103$ ($T - O$)

$U = 52$ ($\Sigma_{i=1..10}\ U_i = 6 + 12 + 6 + 1 + 5 + 5 + 5 + 2 + 3 + 7$)

$M = 51$ ($N - U = 103 – 52$)

$A = 29$ ($\Sigma_{i=1..10}\ A_i = 0 + 0 + 0 + 0 + 0 + 4 + 0 + 0 + 15 + 10$)

$P = 0$

$C = 22$ ($51 – 0 – 29$)

S = 12

R_M = 0.50 (51 / 103)

R_C = 0.43 (22 / 51)

R_P = 0 (0 / 51)

R_A = 0.57 (29 / 51)

R_U = 0.50 (52 / 103)

R_O = 0 (0 / 103)

R_S = 0.18 (12 / 67)

The following observations can be made:

1. Only half of the system data structures are mapped to AP 213 ARM. Those data related to job information and tool assignment are not mapped to AP 213. The concepts of "job" and "tool assignment" are not well represented in AP 213.

2. Similar to Section 4.2.3, the NC process and tool definition data are found in the input to this system. As evidenced by the high ambiguity ratio (0.57), process and tool definitions are repeatedly mapped to two entities: process_parameter and tool_parameter.

3. From the ratio R_S, only 18% of the AP 213 ARM entities are used in the mapping. This means a lot of the system data are mapped to a few ARM entities. From the R_A measure, more than half of the mapped data structures are ambiguously mapped. Those ARM entities that are tool path generation-related data are used in the mapping. Non-tool path related entities that are not used in mapping are, for example, drawing, raw_material_requirement, special_instruction, and validation.

4.2.5 A Summary of Coverage Measurements

The following table summarized the maximum, minimum, and the average of the measures of R_M, R_C, R_P, R_A, R_U, R_O, and R_S in all four systems analyzed from Section 4.2.1 to

Section 4.2.4.

	Maximum	**Minimum**	**Average**
$\mathbf{R_M}$	0.77	0.39	0.55
$\mathbf{R_C}$	1.00	0.01	0.42
$\mathbf{R_P}$	0.00	0.00	0.00
$\mathbf{R_A}$	0.99	0	0.58
$\mathbf{R_U}$	0.61	0.23	0.45
$\mathbf{R_O}$	0.24	0	0.09
$\mathbf{R_S}$	0.43	0.08	0.19

The averages show that the coverage is not high. From the average R_M=0.55, only about half of the system data structures are covered by AP 213. The average uncovered ratio (R_U) is 0.45. From the completeness ratio R_C=0.42, over a half of covered data structures are completely mappable to AP 213. From the average R_P=0, there are no partially mapped data structures because most data structures are broken down to data elements and mapped to attributes in AP213 ARM entities. However, from R_A=0.58, on average more than a half of mappable data structures are ambiguously mapped because the definitions of the data structures are close to, but not exactly the same as, the definitions in AP 213 ARM. From average R_O = 0.09, only a few of system data structures are out of the scope of AP 213. Lastly, from average R_S = 0.19, about 20% of ARM entities are used in mapping. Most of AP213 ARM entities are not relevant to the four systems. This is because there are only a few process planning-related data structures in the two NC programming systems.

4.3 Observed AP213 Limitations

In another independent effort, an analysis of the Application Interpreted Model (AIM) was conducted at AlliedSignal, and several problems were found in the AIM [10]. They are described as follows:

1. It lacks hiearchical and sequencing entities for Actions,
2. Additional Action_Methods are needed for manufacturing processes, e.g., there is a Part_Loading but not a Part_Unloading Action_Method. Additionally, Action_Hierarchy, Action_Relationship, Action_Sequence, Drill, Finish_end_mill, Marking, Produce_product, Production_Operation, Rough_end_mill, Saw, Semi_finish_end_mill, Spot_drill, Approval_date_time, Product_Category_Relationship, etc. have been identified as missing from AP 213 by Allied Signal, and
3. Many AIM entities and types were identified as missing from the AIM in AP 213. They are documented in Tables 2 – 4 in [10].

From our analysis, a major problem of the ARM is that several entities are defined to represent very general concepts, resulting in mapping ambiguity. Multiple system data elements with specific concepts have to be mapped to one ARM entity. Example overly used ARM entities are *Performance_rate, Activity, Material_parameter, Machine_parameter, Tool_parameter, and Process_parameter*. This heavy reuse results in high R_A ratios. This ambiguity problem makes it difficult to precisely transfer data from one system to another using AP 213. In Allied Signal's report, this kind of ambiguity problem in Action_Method was also documented in Finding 2 above. Many NC machining operations must be mapped to Action_Methods. Examples of the NC machining operations can be found in Tables 1- 4 in the Appendix. Only a few subactivities (Material_removal, Part_loading, Part_handling, Machine_setup, Validation, and Ancilliary_action) of the Activity entity are defined in the ARM. A more detailed Activity (or Action_method) hierarchy is needed in order to unambiguously transfer operation definitions from one application system to another using AP 213.

The design information of a machined part is required as basic input data to both CAPP and CAM systems. Different CAPP and CAM systems have different requirements for part information. Some systems require stock, final part shape, tolerance, and surface finish information to calculate machined volumes. Other systems need surfaces and tolerance information. There are no clear definitions on stock, finish shape, machined volume, and intermediate shape in AP 213. AP 213 ARM should provide clear paths that link stock and machined features data to entities that define machining operations.

AP 213 ARM lacks the ability to capture tool name. No tool name attribute is provided by the ARM. Tool name, as the identifier for a tool, is used in several system data structures. Furthermore, the ARM lacks clear definitions on tool parameters, which are connected with tool assembly. Tool assembly elements should also have tool assembly parameters.

Finally, the concept of data file and document related information should be in the AP 213 ARM. Data files such as NC files and process plan files are often captured in system data. Entities to clearly define the piece of information of the location and properties of a file are essential in data exchanging and sharing between CAPP and NC programming systems, but no file name attribute is specified in the ARM. For further improvement of the AP 213 ARM, we suggest that ISO 14649 Part 11 [11], which is in Committee Draft (CD) Status, as well as CAPP and CAM system interfaces, and industrial practices should be reviewed.

5 CONCLUSION

AP 213 is in Final Draft International Standard (FDIS) status. It is important to verify the application protocol using commercial systems to demonstrate the applicability of the standard to the state of the art technology. By examining the AP 213 Application Reference Model and the interface data of the four commercial systems, we identified the areas in the ARM that are insufficient to cover the system data and are ambiguous in representing some system data. Conclusions can be drawn as follows:

1) The AP 213 ARM supports the representation of each of the selected application systems to a limited extent. Limitations vary for the different systems. The limitations are indicated by the ratios in the coverage analysis. In general, low

coverage is shown for the systems.

2) A large amount of ambiguity is found in the mapping. This is caused by AP 213 ARM entity definitions that are too generic and vague, i.e., not specific enough to represent fine concepts.

3) There are critical philosophical differences in incorporating the concept of NC machining process plans in the four commercial systems. In process planning systems, machined areas are considered as features (volume to be removed). In NC programming systems, machined areas are defined by surfaces (in Boundary Representation). The AP 213 ARM does not provide a mechanism to identify which surfaces in the feature are machined and which ones are used to stop the tool (usually referred as check surfaces). Similarly, process planning systems are concerned with tool assemblies while NC programming systems are concerned with tool slot numbers. This discrepancy results in different definitions for tool length.

4) Problems in the AIM have been identified and documented by the project “A Process Definition Repository Based on STEP AP 213” conducted by a technical team at Allied Signal Aerospace.

6 REFERENCES

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APPENDIX